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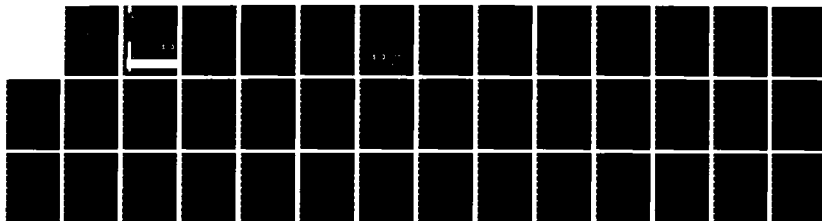
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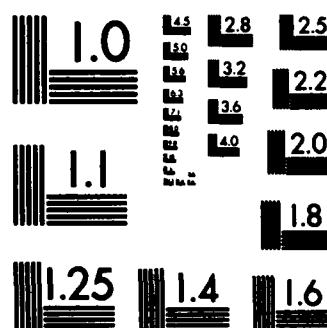
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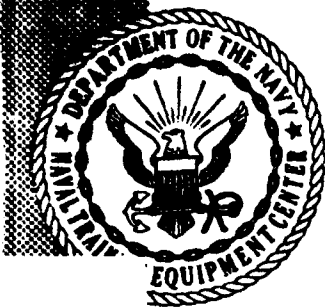


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Technical Report NAVTRAEQUIPCEN 80-D-0014-0019-1

A PILOT/VEHICLE MODEL ANALYSIS OF THE  
EFFECTS OF MOTION CUES ON HARRIER CONTROL TASKS

Bolt Beranek and Newman Inc.  
10 Moulton Street  
Cambridge, MA 02238

September 1983

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→ these conditions and the level of pilot attention and/or skill (or training) was investigated by means of a sensitivity analysis in which we systematically varied a parameter of the OCM (the observation noise/signal ratio) which can be related to these pilot factors.

The results indicate that motion cues could be very significant in the Harrier hover control task for the augmented (SAS-OFF) vehicle. For hover with the SAS-ON and for cruise flight, motion cues are predicted to be, at best, of marginal utility for improving performance. The model results suggest that motion cues may be provided for these tasks by a g-seat with little loss in performance as compared to using platform motion. However, the assumptions underlying the g-seat analysis have not been verified experimentally.



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## FOREWORD

As models of piloting control incorporate more variables that broaden the scope of their predictions about vehicle control, the models' potential for becoming tools for device specification increases. The generality required for such use rests upon the data to which a model has been fitted as well as the model's ability to generate predictions about new situations.

Recently, Bolt Beranek and Newman Inc. developed the mechanism for their Optimal Control Model (OCM) to predict pilots' simulator control performance when the simulation includes various g-cueing devices (motion platforms and g-seats), and the present work extends these predictions to a new vehicle and a new set of flying tasks. NAVTRAEQUIPCEN 80-C-0055-1 reported the fitting of the OCM to g-cueing data from a helicopter hover task, and this report extrapolates those results to the control of a new airframe (the AV-8B) and to a set of different flying conditions. The purpose of this work was to examine the utility of motion cueing for the tasks which a training simulator for the AV-8B would have to support. In addition, a sensitivity analysis revealed the model's ability to support inferences about training procedures using such a device. Both of these efforts demonstrate the power an engineering model can have for the analysis of potential configurations of a training device.

*G. L. Ricard*

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Scientific Officer

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## SECTION I

## INTRODUCTION

The need for motion cues in flight simulators has been a subject of much debate in recent years. Although pilots invariably prefer the richer, more realistic, cue environment provided by well-designed platform motion systems, the actual improvement of performance or training effectiveness that results from incorporating these expensive devices has been questioned.

A fundamental problem in determining the requirement for motion cues for a particular simulation is that there is no universal, simple set of rules for predicting the impact or cues, although some general indications of when simulator motion is important have been identified.<sup>1</sup> A prime difficulty is that the magnitude of the effects of motion cues on performance depends critically on the specifics of the task; i.e., on the vehicle dynamics, or the nature of the disturbances, or the task requirements, the displays, etc. For this reason, several recent research efforts have focused on the development and use of a closed loop pilot/vehicle model, the multi-cue optimal control model (MC-OCM), to predict the effects of motion and other cues on performance.<sup>2-5</sup> The results of these studies suggest that this model can indeed be useful for exploring the impact of various cues on both performance and workload.

In this report, we summarize the results of applying the MC-OCM to a number of flight control tasks for the Harrier AV-8B. The effects of providing motion cues via an idealized platform motion system or a g-seat device are predicted with the model, and the results are shown to depend on flight condition and on the presence or absence of the stability augmentation for the aircraft. In addition, these results are sensitive to a parameter of the pilot model that relates to the attention devoted to the task and/or to the pilot's level of skill.

---

1. J. A. Puig, W. T. Harris, and G. L. Ricard, "Motion in Flight Simulation: An Annotated Bibliography," NAVTRAEQUIPCEN IH-298, July 1978.

2. W. H. Levison and A. M. Junker, "A Model for the Pilot's Use of Motion Cues in Steady-State Roll Axis Tracking Tasks," presented at AIAA Flight Simulation Technologies Conference, Arlington, TX, Sept. 1978, AIAA Paper No. 78-1593.

3. S. Baron, R. Lancraft and G. Zacharias, "Pilot/Vehicle Model Analysis of Visual and Motion Cue Requirements in Flight Simulation," NASA CR-3312, October 1980.

4. S. Baron, "A Multi-Cue OCM for Analysis of Simulator Configurations," Bolt Beranek and Newman Inc., Report No. 4374, April 1980.

5. S. Baron, "An Optimal Control Model Analysis of Data from a Simulated Hover Task," NAVTRAEQUIPCEN 80-C-0055-1, May 1981.

## SECTION II

## TASK DESCRIPTION

The effects of motion cues on AV-8B flight control performance were analyzed with the MC-OCM. In this section, the assumptions used in arriving at the closed-loop pilot/vehicle model are described.

## GENERAL FLIGHT CONTROL TASKS

The tasks considered were maintenance of hover position in turbulence and attitude regulation in high-speed cruise. The flight conditions corresponding to these two tasks are given in Table 1. Six degree-of-freedom aircraft dynamic equations of motion were linearized about these conditions to provide the vehicle dynamics for the MC-OCM analysis. This resulted in decoupled longitudinal and lateral control tasks.\* The high-speed cruise task was simplified further by using the short period approximation for the longitudinal task.

The AV-8B is equipped with a stability augmentation system (SAS). The SAS provides for two modes of operation: low-speed and high-speed. For our studies, the low-speed mode was used only for the hover condition, and the high-speed mode was used only for the cruise condition.

The low-speed longitudinal SAS provides for direct pitch stick feed-through to the stabilator and fore/aft Reaction Control Valves (RCV's). Direct pitch-rate feedback augments the stick signal to increase short-period damping.

The low-speed lateral/directional SAS provides for direct roll stick feed-through to the ailerons and roll RCV's, and for direct rudder pedal feed-through to the rudder and yaw RCV's. For lateral control, the roll stick signal is augmented by direct roll-rate feedback, to improve damping. For directional control, the rudder pedal signal is augmented by washed-out yaw-rate feedback, to improve damping and allow for steady turns. Additional augmentation of the rudder pedal signal is provided by band-pass filtered lateral acceleration and a roll-to-yaw interconnect obtained by low-pass filtering the roll stick signal; both serve to improve turn coordination.

The high-speed longitudinal SAS inhibits RCV activity, and replaces the direct pitch rate feedback with washed-out pitch rate feedback. This provides for improved short-period damping while allowing zero effective SAS stick-force-per-g during steady pullups and turns.

\* Stability derivatives for the linearized equations were obtained from Mr. Thomas Lacey of McDonnell Douglas Corporation, St. Louis, MO 63166.

TABLE 1. TRIM FLIGHT CONDITIONS

PARAMETER	UNITS	HOVER	CRUISE
CONFIGURATION	-	1	2
ALTITUDE	FT	50.0	2000.0
MACH	-	0.001	.70
NORMAL ACCELERATION	G's	1.0	1.0
DYNAMIC PRESSURE	PSAF	.001	333.8
AIRSPEED	KTAS	.7	429.8
ANGLE OF ATTACK	deg	7.30	3.19
GEAR	-	DOWN	UP

The high-speed lateral/directional SAS inhibits RCV activity, but still provides for direct roll stick and rudder pedal feed-through to the ailerons and rudder. As in the low-speed lateral SAS, the roll stick signal is augmented by direct roll-rate feedback. For directional control, the roll-to-yaw interconnect is eliminated and, instead of providing filtered lateral acceleration and yaw rate feedback, a sideslip rate feedback signal is used to augment the rudder signal to improve dutch roll damping and turn coordination. This signal is estimated from angle-of-attack, lateral acceleration, and the roll and yaw rates.

In the analyses conducted here, the effects of motion cues on performance were investigated for both the augmented (SAS-ON) and unaugmented (SAS-OFF) configurations.

#### DISTURBANCES

Gust disturbances for both hover and cruise were determined

from the Dryden gust model.<sup>6</sup> The turbulence velocities were applied to the airplane equations of motion through the aerodynamic terms. Both uniform gust immersion and penetration effects were included (the latter by means of angular velocity gusts). Thus, for the longitudinal analyses  $u_g, w_g$  and  $q_g$  gusts were employed and for the lateral-directional analyses  $v_g, p_g$  and  $r_g$  gusts were used. Root-mean-square gust intensities were selected as a function of altitude to correspond to clear air turbulence levels that can only be exceeded or equalled with a probability of 0.01.<sup>7</sup> Thus, the wind intensities were quite severe and predictions of performance should be judged accordingly.

#### DISPLAYED VARIABLES

For the hover task, it was assumed that visual information would be obtained from a simulated external scene. The approach used to model the scene information was identical to that used by Baron, et al.<sup>8</sup> Thus, attitude variables ( $\theta, \psi, \phi$ ) and position errors ( $x, y, z$ ), as well as the rates of change of these variables, were assumed to be available visually. In the cruise condition, it was assumed that attitude and attitude-rate information was available from an appropriate cockpit display.

Platform motion was assumed to provide cues of specific force and of angular velocities and accelerations. The g-seat was assumed to provide a cue of specific force for surge motions and pitch and roll angular velocities and accelerations. These cue sets are identical to those assumed by Baron.<sup>9</sup> Because specific hardware was not being evaluated, no simulation hardware dynamics or delays were included in the model. Thus, the cues are assumed to be presented faithfully and one can view the corresponding results for the platform motion condition as being representative of an ideal simulation, or of flight.

#### Parameters of MC-OCM Pilot Model

The MC-OCM pilot/vehicle model is shown in Figure 1. This model has been documented extensively elsewhere<sup>10</sup> and its application to the analysis of perceptual cues was discussed in

6. Anon. "Military Specification-Flying Qualities of Piloted Airplanes," MIL-F-8785B (ASG), May 1968.

7. Ibid.

8. See footnote 3 on p. 5.

9. See footnote 5 on p. 5.

10. S. Baron and W. H. Levison, "The Optimal Control Model: Status and Future Directions," Proceedings of International Conference on Cybernetics and Society, Cambridge, MA, October 1980.

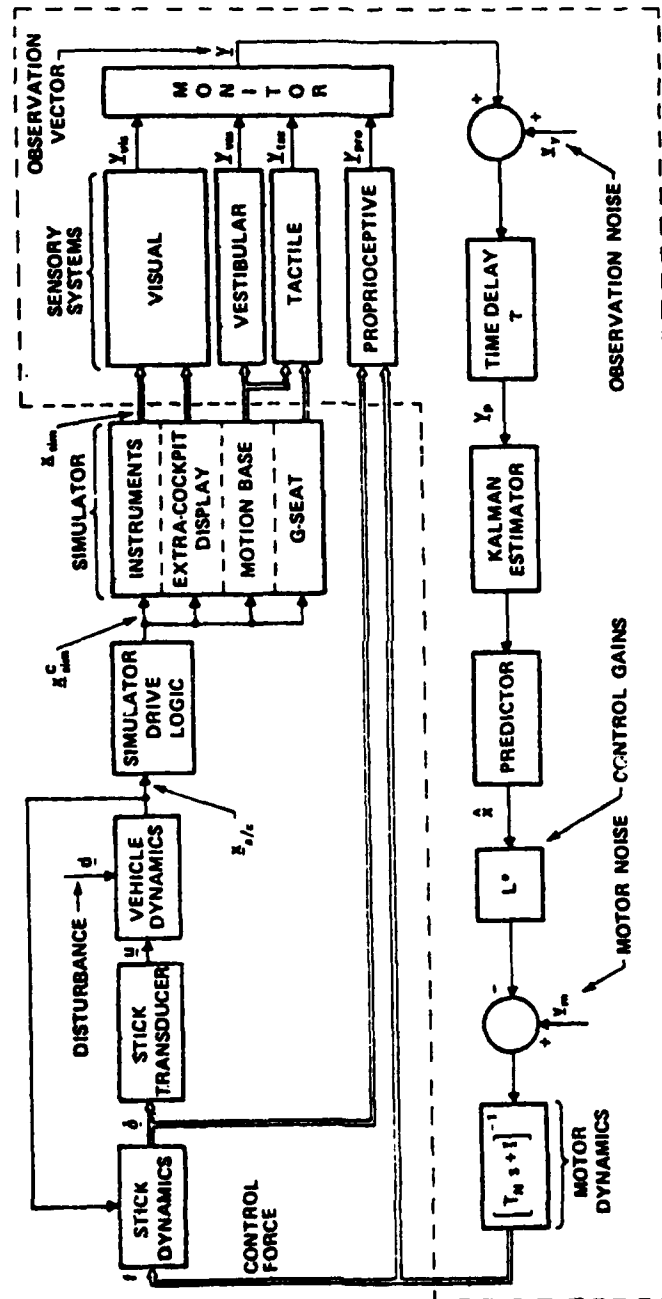


Figure 1. Pilot/Simulator Model

detail by Baron.<sup>11</sup> Here, we simply indicate the parameter values used in this study. The parameters of interest are the cost functional weightings that are used to account for the control objectives, the pilot's time delay, and the observation- and motor- noise-to-signal ratios.

The MC-OCM assumes that the well-trained, motivated pilot will choose his control strategy to minimize a cost functional that is a weighted sum of mean-squared outputs and controls:

$$J = \sum_i \overline{q_i y_i^2} + \sum_j (\overline{r_j u_j^2} + \overline{g_j \dot{u}_j^2}) \quad (1)$$

where  $y_i$  and  $u_j$  are vehicle outputs and pilot control inputs, (.) indicates time derivative and the bar indicates expected value. This cost functional is a generalization of the mean-squared error criterion used extensively in the analysis of tracking performance. The weightings on outputs and control deflections are generally determined from system performance objectives or constraints. The weightings on the control-rate term, (the  $g_j$ 's) are selected to yield "desired" neuro-motor time constants for the model; these time constants reflect either an inherent bandwidth constraint of the pilot or a subjective penalty on unnecessarily excessive control rates.<sup>12</sup>

For the hover control tasks, weightings on output variables (position and velocity errors, attitude and attitude-rate variables) and neuro-motor time constants were chosen on the basis of previous modelling studies of precision hover control.<sup>13,14</sup> The weightings on control deflections were based on deflection limits for the AV-8B. The resulting cost function parameters and neuro-motor time constants are given in Table 2. Note that the weightings are dimensioned so as to yield a non-dimensional performance index,  $J$ , and that a weighting on position error of  $(\frac{1}{5\text{ft}})^2$  implies a contribution to total cost of one unit for a 5ft.<sup>5</sup> rms position error, and so on.

For the cruise control task, a much simpler cost functional was selected; specifically, the task was viewed as one of minimizing attitude errors in the presence of gusts; control-rate weightings were selected to yield neuro-motor time constants of .1 seconds.<sup>15</sup> Thus, the cruise control task was viewed as

11. See footnote 5 on p. 5.

12. D. L. Kleinman, S. Baron, and W. H. Levison, "An Optimal Control Model of Human Response, Part I: Theory and Validation," Automatica, Vol. 6, pp. 357-369, 1970.

13. W. C. Hoffman, D. Kleinman, and L. Young, "Display/Control Requirements for Automated VTOL Aircraft," ASI-TR-76-39, October 1976.

14. See footnote 3 on p. 5.

15. See footnote 12.

TABLE 2. COST FUNCTIONAL WEIGHTINGS FOR HOVER CONTROL TASK

	VARIABLE	$\left( \frac{1}{\text{WEIGHTING FACTOR}} \right)^{1/2}$	NEUROMOTOR TIME CONSTANT
L O N G I T U D I N A L	x	5 ft.	
	$\dot{x}$	1 ft./sec.	
	z	5 ft.	
	$\dot{z}$	1 ft./sec.	
	$\theta$	1 degree	
	$\dot{\theta}$	.5 degrees/sec	
	$\delta_e$	3 degrees	.15 seconds
	$\delta_T$	10 (% Full Throttle)	.2 seconds
L A T E R A L	y	5 ft.	
	$\dot{y}$	1 ft./sec.	
	$\phi$	10 degrees	
	$\dot{\phi}$	.5 degrees/sec	
	$\psi$	1 degree	
	$\dot{\psi}$	.5 degrees/sec	
	$\delta_A$	--	.1 seconds
	$\delta_R$	--	.1 seconds



analogous to wide-band precision tracking tasks studied in the laboratory. This approach has proven to be successful in the past for analyzing tracking with high performance aircraft.<sup>16</sup>

The remaining parameters of the pilot-model are the time delay, motor noise/signal ratio and observation noise/signal ratio. The time delay was set at .2 seconds and the motor noise/signal ratio at -25 dB, values that are essentially "nominal" for the MC-OCM.<sup>17</sup>

Observation noise is a key aspect of the OCM as it is the principal means in the model for accounting for the portion of the human's response that is random, i.e., that is uncorrelated with the input forcing function. (The motor noise also contributes to this portion of the operator's response but, in general, to a lesser extent). The observation noise is analogous to the internal noise postulated in signal detection theory and it provides one means by which the model can mimic human limitations in information processing and attention capacity.

It is assumed in the OCM that each perceived variable,  $y_i$ , is corrupted by a white (wide-band), gaussian noise,  $v_{y_i}$ , with autocovariance,  $V_i$ , that scales with the mean-squared signal level. Thus, for time-invariant systems in steady-state, which is the situation of interest here, we have

$$V_i = \pi P_i \left[ \frac{y_i^2}{N(y_i^2, a_i)} \right] \quad (2)$$

where  $P_i$  is the observation noise signal ratio associated with perception of  $y_i$  and  $N(y_i^2, a_i)$  is the random-input describing function for a constant threshold,  $a_i$ , which is included to account for display or perceptual resolution effects. (This threshold may also be used to account for pilot "indifference" to "small" errors.)

Because the observation noise/signal ratio is relatively constant across a variety of tracking tasks, we interpret this model parameter as a reflection of the human operator's central-processing capability. This association leads to a relatively straightforward model for task interference and operator workload.<sup>18</sup> Very briefly, we consider, for

16. S. Baron, "A Model for Human Control and Monitoring Based on Modern Control Theory," Journal of Cybernetics and Information Sciences, Vol. 1, Number 1, Spring 1976.

17. See footnote 13 on p. 10.

18. W. H. Levison, "A Model for Mental Workload in Tasks Requiring Continuous Information Processing," Mental Workload Its Theory and Measurement, Plenum Press, New York and London, 1979.

convenience, that attention-sharing may be required at two levels: between control-related (including monitoring of automatic control performance) and non-control tasks; and among the displays required for performing the control task. For example, a pilot might share attention between control and communication and, while controlling, between flight path and attitude displays. When motion cues are available, one might also assume that attention is shared between visually-presented display variables as a group and "display" variable supplied by motion sensors (see below). Thus, we define

$f_t$  = fraction of attention devoted to the control task as a whole

$f_i$  = fraction of attention devoted to the  $i^{\text{th}}$  display in sub-task  $s$

Then, the effects of attention-sharing are modelled by an increase in the "nominal" noise/signal ratio, i.e., by

$$P_i = \bar{P}_0 \cdot \frac{1}{f_t} \cdot \frac{1}{f_i} \quad (3)$$

where  $P_i$  is the noise signal ratio associated with the  $i^{\text{th}}$  display when attention is being shared and  $\bar{P}_0$  is the base, or nominal, noise/signal ratio corresponding to full attention being devoted to the display. The fractional attentions are all  $\leq 1$  and  $\sum_i f_i = 1$ .

To predict the effect on specific tasks of sharing attention, model solutions are used to determine the optimum allocation of attention, which, in line with the fundamental optimality hypothesis, is taken as a prediction of the pilot's allocation. This model for task interference has been validated for both control tasks and for monitoring tasks.

Once the allocation of attention among display variables ( $f_i$ ) has been determined, the model can be used to predict the tradeoff between system performance and attention to the tracking task as a whole ( $f_t$ ). In this context, the value of  $f_t$  necessary to achieve a criterion level of importance is taken to be an indicator of the "attentional workload" of the tracking task.

The base noise level,  $\bar{P}_0$ , may be related to skill or training level, with higher noises obviously associated with lower skill or lesser levels of training. This reflects the observation that, in a tracking task, well-trained subjects tend to be highly selective in their control actions, when compared with their untrained counterparts. That is, their control actions tend to be more highly correlated with the disturbance they are attempting to regulate, and less dominated by irrelevant or uncorrelated control actions, actions which serve little or no use in regulating the disturbance. In effect, the well-trained subject is less "noisy" than his untrained or poorly-trained counterpart.

One might ascribe this noise reduction trend with training to a number of factors, but the parallels seen in detection theory experiments<sup>19</sup> suggest that improvements in perceptual efficiency might conveniently account for the overall noise reduction trends. If a subject becomes perceptually more efficient with training, then we may relate the increased efficiency to a reduction in perceptual "noise" which results in compensatory control actions that are correspondingly less noisy. In summary, we are suggesting that the reduction in uncorrelated control actions with training can be traced, at least in part, to a gradual improvement in the subject's perceptual efficiency and this, in turn, can be modelled in the OCM by a reduction in observation noise/signal ratio. Thus the model interpretation of training trends is quite straightforward: subjects begin training with relatively high observation noise levels, which result in poorly correlated control actions; after training, subjects have managed to reduce their observation noise levels, and are capable of producing highly correlated control actions. This notion has received some empirical support in a recent study of learning effects in a roll-axis tracking task.<sup>20</sup>

It is clear from equation (3), however, that the results of changes in  $P_o$  are indistinguishable from those of changes in  $f_t$ . Therefore, in the present effort, we combined these parameters by rewriting equation (3) as

$$P_i = \frac{P_o}{f_i} \quad (4)$$

where

$$P_o = \frac{\bar{P}_o}{f_t} \quad (5)$$

$P_o$ , which relates to both level of attention devoted to the task and level of skill or training, was then used as a parameter of the study. This quantity was varied from  $P_o = -20\text{dB}$  to  $P_o = -11\text{dB}$  for sensitivity analyses. The value of  $-20\text{ dB}$  corresponds to the average observation noise/signal ratio measured in single-axis, laboratory tracking tasks in which subjects are highly practiced and well motivated;<sup>21</sup> the effort involved in these situations is substantial and a requirement to sustain such a level of attention to the manual control task over other than short or moderate periods of time would probably be undesirable for realistic tasks.

19. D. M. Green and J. A. Swets, "Signal Detection Theory and Psychophysics," New York, J. Wiley and Sons, 1966.

20. W. H. Levison, R. E. Lancraft, and A. M. Junker, "The Effects of Simulator Delays on Performance and Learning in a Roll-Axis Tracking Task," Proceedings of Fifteenth Annual Conference on Manual Control, Wright State Univ., Dayton, OH, March 1979.

21. See footnote 12 on p. 10.

The fractional attention,  $f_i$  in equation (3), reflect the selective aspects of attention. We assume that attention need not be shared between cues or displays provided by different sensory modalities. The pilot is assumed to share attention among the visual displays (e.g., because of scanning). Whether or not attention must be shared among different motion cues has not been established unequivocally, so results were obtained for both assumptions. For g-seat cues, only the optimistic assumption of no sharing of attention was examined. Thus,

$$\sum_i f_i^{\text{vis}} = 1$$

either

$$\sum_i f_i^{\text{MB}} = 1, \text{ or } f_i^{\text{MB}} = 1 \text{ for all } i.$$

and

$$f_i^{\text{gST}} = 1 \text{ for all } i.$$

where the superscripts refer to the source of the cues. Note that it is assumed that no additional pilot attention is required to obtain derivative information from an indicator or cue.<sup>22</sup> Where attention sharing was assumed to be required, the fractional attentions were determined in this study so as to optimize performance.<sup>23</sup>

The final parameters needed to determine the  $V_i$ 's in equation (2) are the perceptual thresholds,  $a_i$ . These threshold were determined for the hover condition using the method described in Baron, Lancraft and Zacharias<sup>24</sup> and in Baron.<sup>25</sup> The resulting thresholds are given in Table 3. For cruise, visual thresholds of .05° and .20°/sec were used for attitude and attitude-rate variables, respectively; these correspond to values obtained from tracking experiments in which idealized electronic visual displays of error were provided.<sup>26</sup>

In summary, parameters of the pilot model were chosen and fixed largely on the basis of previous studies. The parameter corresponding to the basic observation noise/signal ratio of the pilot was allowed to vary to explore the sensitivity of performance to this important factor as a function of the cue environment.

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22. Ibid.

23. D. L. Kleinman, "Solving the Optimal Attention Allocation Problem in Manual Control," IEEE Trans. on Automatic Control, Vol AC-21, No. 6, Dec 1976.

24. See footnote 3 on p. 5.

25. See footnote 5 on p. 5.

26. W. H. Levison, "The Effects of Display Gain and Signal Bandwidth on Human Controller Remnant," AMRL-TR-70-93.

TABLE 3. PERCEPTUAL THRESHOLDS \*

Variable	Visual	Motion Platform	G-Seat
$x$ , ft	4.2	--	--
$\dot{x}$ , ft/sec	1.05	--	--
$y$ , ft	.04	--	--
$\dot{y}$ , ft/sec	.17	--	--
$z$ , ft	1.85	--	--
$\dot{z}$ , ft/sec	.50	--	--
$a_x$ , ft/sec <sup>2</sup>	--	.053	.0636
$a_y$ , ft/sec <sup>2</sup>	--	.053	--
$a_z$ , ft/sec <sup>2</sup>	--	.053	--
$\phi$ , deg	.02	--	--
$\dot{\phi}(p)$ , deg/sec	.09	2.5	3.0
$\ddot{p}$ , deg/sec <sup>2</sup>	--	.41	.49
$\theta$ , deg	.05	--	--
$\dot{\theta}(q)$ , deg/sec	.20	3.6	4.3
$\ddot{q}$ , deg/sec <sup>2</sup>	--	.67	.80
$\psi$ , deg	.05	--	--
$\dot{\psi}(r)$ , deg/sec	.20	4.2	--
$\ddot{r}$ , deg/sec <sup>2</sup>	--	.41	--

\* An entry of -- means that it is assumed that no information on the variable is provided by the modality

## SECTION III

## RESULTS

Performance predictions were obtained with the OCM for twenty-four flight/motion cueing conditions corresponding to the possible combinations of the following.

Longitudinal Lateral	Hover CRUISE	SAS-ON SAS-OFF	FIXED BASE PLATFORM MOTION G-SEAT
~~~~~	~~~~~	~~~~~	~~~~~
AXIS OF CONTROL	FLIGHT CONDITION	SAS CONDITION	MOTION CUEING CONDITION

In what follows, results for the hover and cruise conditions are discussed separately.

## HOVER

Figures 2-5 present the results of the analysis for the hover condition. In Figure 2, the square-root of the performance index J (Equation 1 with weights from Table 2) is plotted against pilot observation noise/signal ratio for longitudinal (Figure 2a), lateral (Figure 2b) and combined (Figure 2c) control conditions. For each of these flight conditions, SAS-ON and SAS-OFF and fixed base and platform motion cueing are compared. It should be noted that the performance index J has been correlated with pilot ratings by Hess.<sup>27</sup> In addition, using the square root of the performance metric is analogous to plotting rms errors rather than mean-squared errors.

Figure 2a shows that the SAS-ON configuration is much less sensitive to observation noise (i.e., pilot attention or skill level) than the SAS-OFF configuration. This is not surprising and verifies the improvement in handling quality provided by the SAS. It can also be seen that the performance improvement provided by motion cues for the longitudinal control, SAS-ON case is minimal and probably within pilot variability. On the other hand, motion is important for the longitudinal SAS-OFF case, particularly at high (more negative) observation noise/signal ratios. In particular, at a noise/signal ratio of -11 dB, performance for the fixed-base condition is eighty-three (83) percent worse than for the motion-base condition.

Similar effects are observed for the lateral hover control task except that the differences between fixed-base and platform motion cueing conditions are accentuated. For the SAS-ON configuration, platform motion cues are not very helpful (less

27. R. A. Hess, "Prediction of Pilot Opinion Ratings Using an Optimal Pilot Model," Human Factors, Vol. 19, No. 5, 1977.

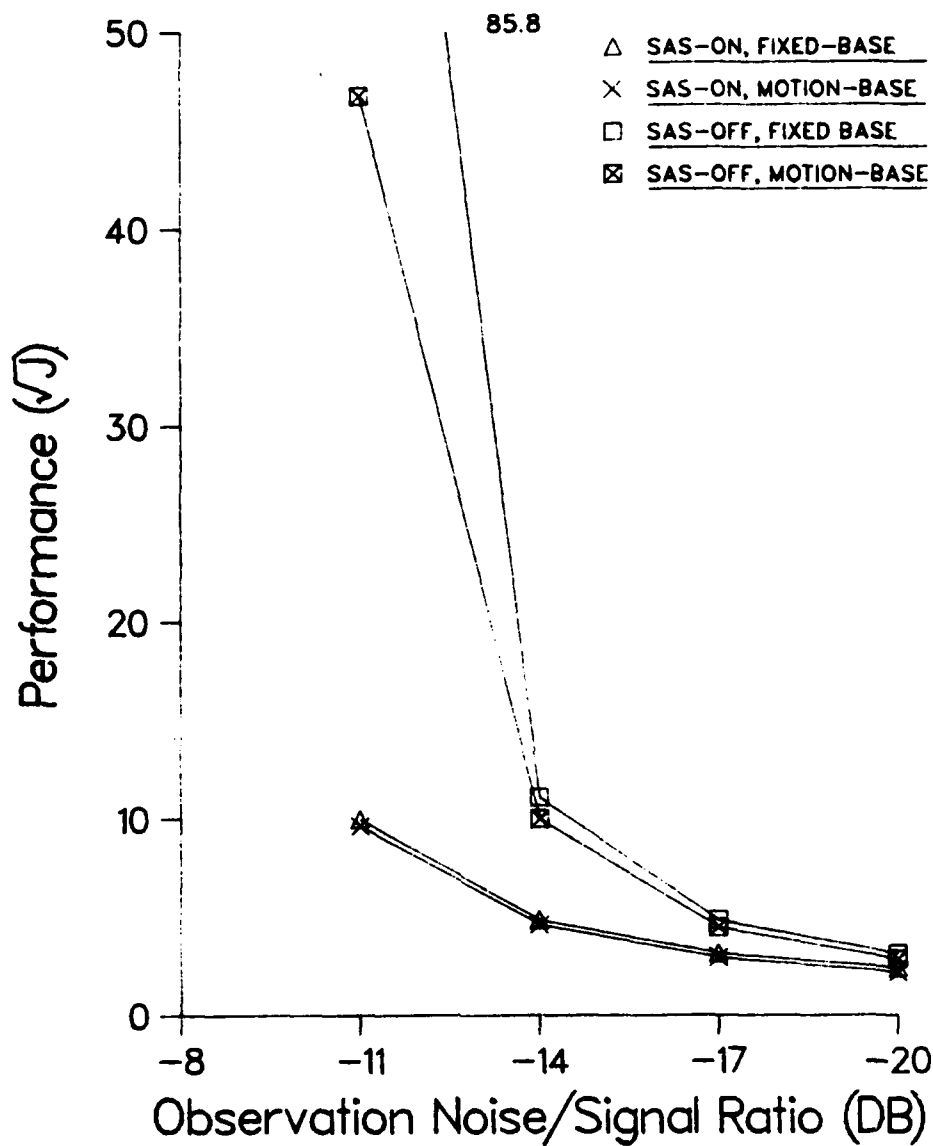


Figure 2. Effect of Platform Motion and Augmentation Condition on Sensitivity of Hover Performance to Pilot Noise/Signal Ratios

a) Longitudinal Control

than an eleven percent improvement) except at the highest noise ratio considered where a thirty-one percent performance improvement is obtained. For the SAS-OFF configurations the beneficial effects of platform motion are very significant at the higher noise ratios and particularly at the highest noise level considered where the fixed-base performance score is more than 2.5 times that obtained when platform motion cues are assumed to be available.

Figure 2c presents the results for combined lateral and longitudinal control, that is the full six degree of freedom hover task. These results were obtained under the assumption that the pilot would share attention equally between the longitudinal and lateral control tasks but would optimize attentional allocation within each axis of control. Because of the assumed non-interaction between the tasks, the combined results reveal no new trends with respect to the parameters of interest.

The effects of platform motion on state and control variables are also of interest and selected results are presented in Figure 3. In particular, the rms vector hover error ( $\sqrt{x^2+y^2+z^2}$ ), vector angular error ( $\sqrt{\theta^2+\phi^2+\psi^2}$ ), and stabilator- and aileron-control deflections are plotted in Figures 3a-d. As expected, these variables display the same trends as the overall performance scores. However, it should be noted that the SAS-OFF results indicate a virtual loss of control at the highest noise level, particularly without motion.

The above results for the platform motion condition were obtained under the assumption that the pilot would have to share attention among the various motion cues. As noted earlier, the validity of this assumption has not been established. Therefore, results were also obtained utilizing the (more optimistic) assumption that attention-sharing among motion cues is not required. In Table 4, a comparison is presented of the performance predicted for the two assumptions concerning attention-sharing. It can be seen that the differences in performances between the two assumptions range from 12-28%, depending on the condition and the observation noise/signal ratio. This means that if the pilot does not have to share attention within the motion modality, the effects of platform motion will be correspondingly greater. For example, instead of the effect of platform motion being only 6-7% for the SAS-ON condition with  $P_0 = -14\text{dB}$ , it would be 36%; i.e., instead of expecting no discernible effect from platform motion, a significant effect would be anticipated.

The remaining results will be based on an assumption of no attention-sharing in the processing of motion cues (either platform motion or g-seat). Though this assumption is still open



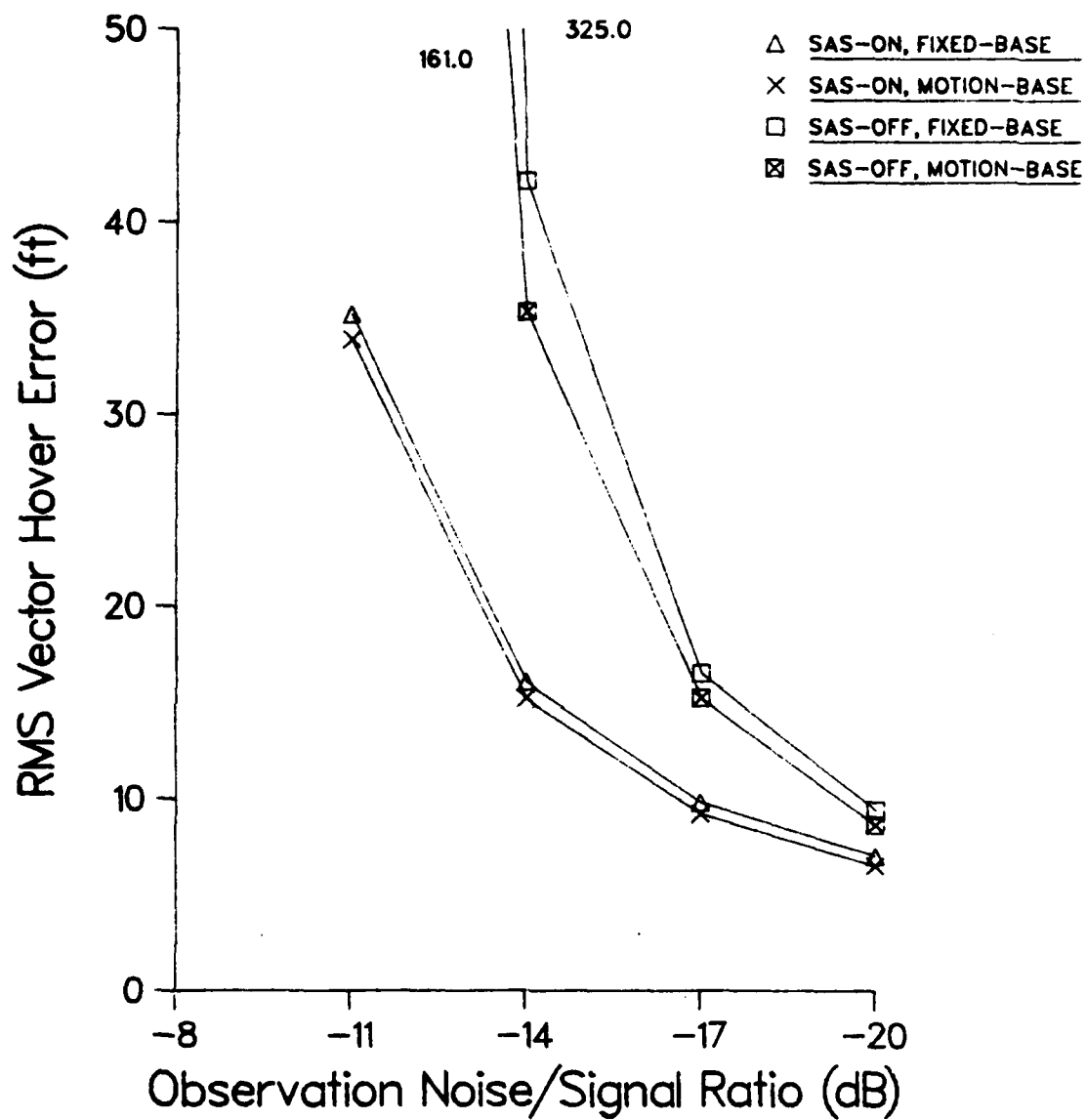


Figure 3. Effect of Platform Motion and Augmentation Condition on RMS Performance Scores

a) Vector RMS Hover Error

TABLE 4. EFFECT OF MOTION CUE ATTENTION-SHARING ASSUMPTION  
ON PREDICTED HOVER PERFORMANCE ( $\sqrt{J}$ )

CONDITION	OBSERVATION NOISE/SIGNAL RATIO $P_o$ (dB)	WITH ATTENTION- SHARING	WITHOUT ATTENTION- SHARING	% CHANGE
SAS-ON	-20	2.86	2.55	12
	-14	5.23	4.09	28
SAS-OFF	-20	3.99	3.51	14
	-14	12.98	11.1	17

to some question, it was used in a previous study<sup>28</sup> and produced results that agreed with experimental data.

A comparison of overall performance ( $\sqrt{J}$ ), and of rms vector hover error for fixed-base, platform motion (no attention-sharing) and g-seat conditions is given in Figure 4. Results are presented for two values of base observation noise/signal ratio,  $P_0 = -14\text{dB}$  and  $P_0 = -20\text{dB}$ . The results for the fixed-base condition are from 20-48 percent poorer than those for the platform motion condition, depending on  $P_0$ . The results for g-seat cueing are generally intermediate between the two other conditions, as could be expected from the assumptions made concerning the quantity and quality of the information provided by such a device. However, the differences between g-seat and platform motion are less than five percent and, therefore, are probably insignificant.

It is also interesting to compare the results for the Harrier to those obtained in the Huey Cobra Study.<sup>29</sup> This is done for rms vector hover error in Figure 5. Both computed model results and experimental data for the Huey Cobra are presented. The data were obtained in an independent experimental study by Ricard, et al.<sup>30</sup> The predicted performance for the Harrier is repeated in the Figure for ease of comparison. All model results are for  $P_0 = -14\text{dB}$ . It can be seen that the results are very similar for the HUEY cobra and the Harrier SAS-ON configuration. However, the effect of motion is significantly more pronounced for the Harrier, SAS-OFF configuration.

## CRUISE

The cruise control task is basically much simpler than the hover task. However, because it is posed as a disturbance regulation task rather than a target tracking task, one might expect motion cues to be of importance for this case, too.<sup>31</sup>

The effects of platform motion on performance are shown in Figure 6 for longitudinal control (Figure 6a), lateral control (Figure 6b) and the combined task (Figure 6c). Recall that for these tasks the performance index,  $J$ , is the sum of mean-squared attitude error and a weighted rms rate of control (where the weight is chosen to yield a neuromotor time constant of .1 seconds). The model results indicated that the attitude errors contributed about ninety percent of the total value for  $J$ .

28. See footnote 5 on p. 5.

29. Ibid.

30. G. L. Ricard, R. V. Parrish, B. R. Ashworth, and M. D. Wells, "The Effects of Various Fidelity Factors on Simulated Helicopter Hover," NAVTRAEQUIPCEN IH-321, January 1981.

31. See footnote 2 on p. 5.

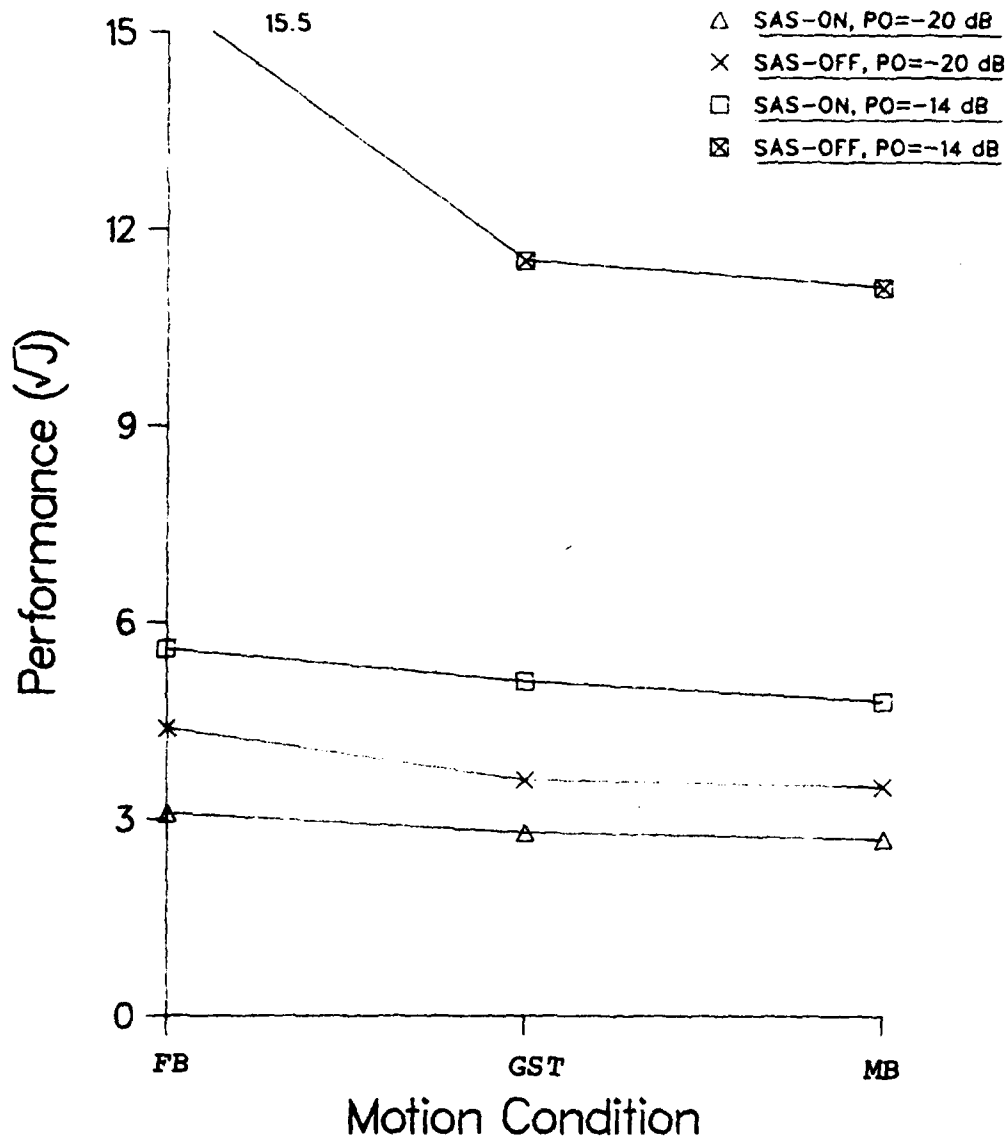


Figure 4. Effect of Motion Condition on Hover Performance

a) Total Performance

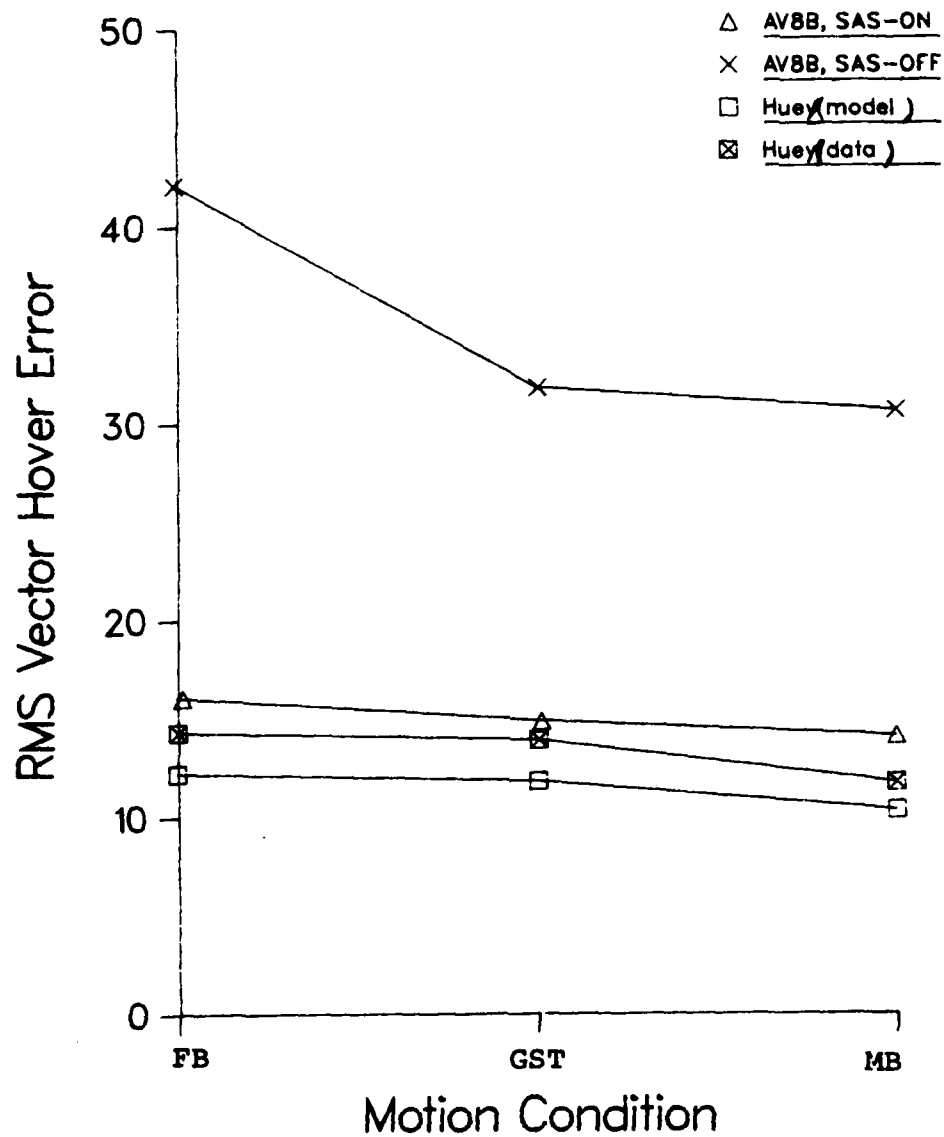


Figure 5. Comparison of Effects of Motion Cues on Predicted Hover Performance of Harrier and Huey Cobra

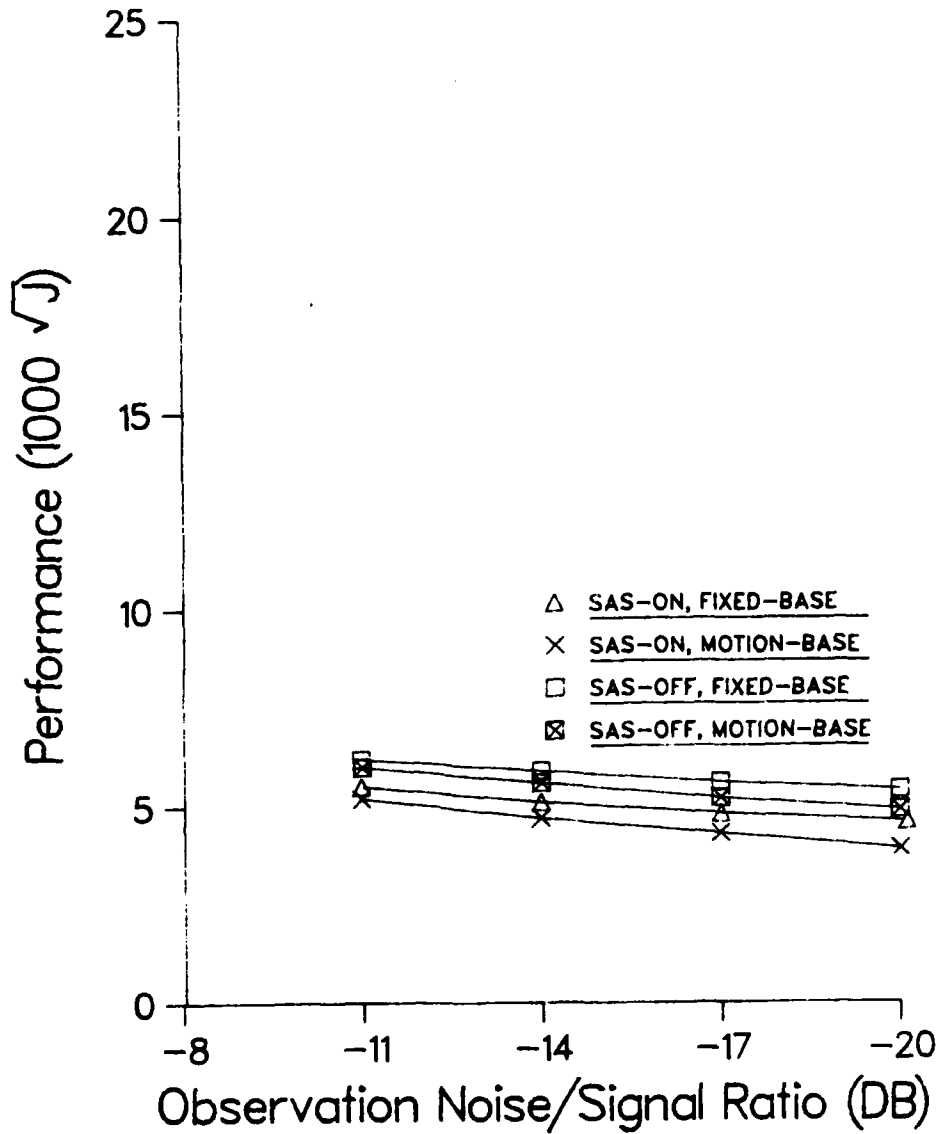


Figure 6. Effect of Platform Motion and Augmentation Conditions on Sensitivity of Cruise Performance to Pilot Noise/Signal Ratios

a) Longitudinal Control

The difference between longitudinal and lateral cruise errors in Figures 6a and 6b is somewhat misleading because the lateral performance involves the sum of two attitude errors (roll and heading) whereas the longitudinal performance incorporates just a single attitude error (pitch). The important point to note from Figure 6 is that the results for cruise are quantitatively and qualitatively different than those for hover. In particular, the maximum effect of motion cueing in cruise is about thirteen percent (compared to > forty percent for hover) and this occurs at the lowest noise/signal ratio ( $P_0 = -20\text{dB}$ ). Because of typical pilot-to-pilot variability, this effect is likely to be barely significant, if at all. In addition, motion cues provide less improvement in performance as  $P_0$  becomes larger, in direct contrast to the hover case. Finally, unlike hover, the cruise results show very little differential sensitivity to observation noise/signal ratio between SAS-ON and SAS-OFF configurations or between motion and fixed-base conditions. These effects are summarized in Figure 7 where the percent change in performance due to removal of motion cues is plotted for the hover and cruise conditions as a function of observation noise/signal ratio.\*

Figure 8 presents the vector angular error for the cruise conditions studied. The results directly parallel those of Figure 6, as expected.

A comparison of performance for the fixed-base, g-seat and platform motion conditions is given in Figure 9. The trend here is the same as for hover.

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\* Note that the sensitivity curves for hover are based on the assumption of sharing attention within the motion modality whereas those for cruise are not.

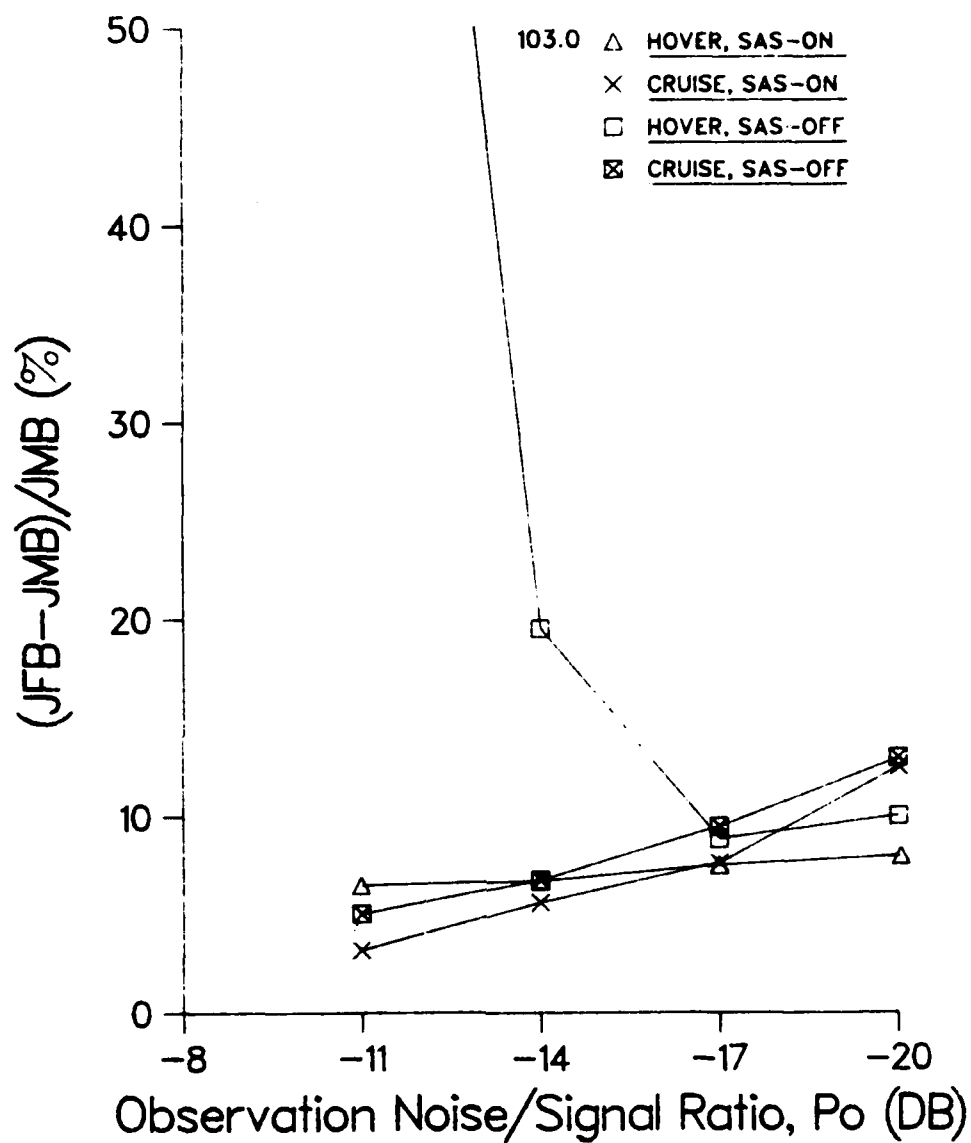


Figure 7. Comparison of Effects of Motion on Hover and Cruise Performance



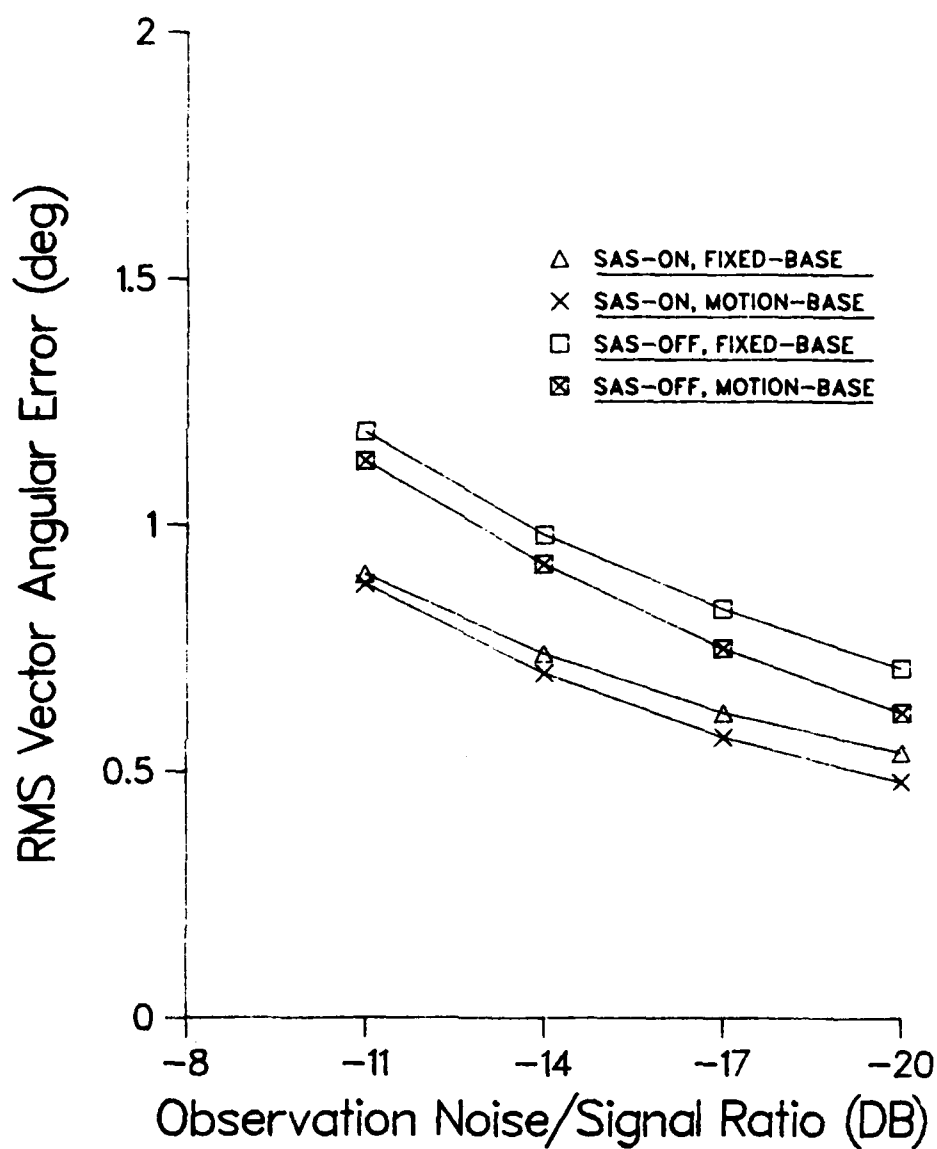


Figure 8. Effects of Platform Motion and Augmentation Configurations on Vector Angular Cruise Error

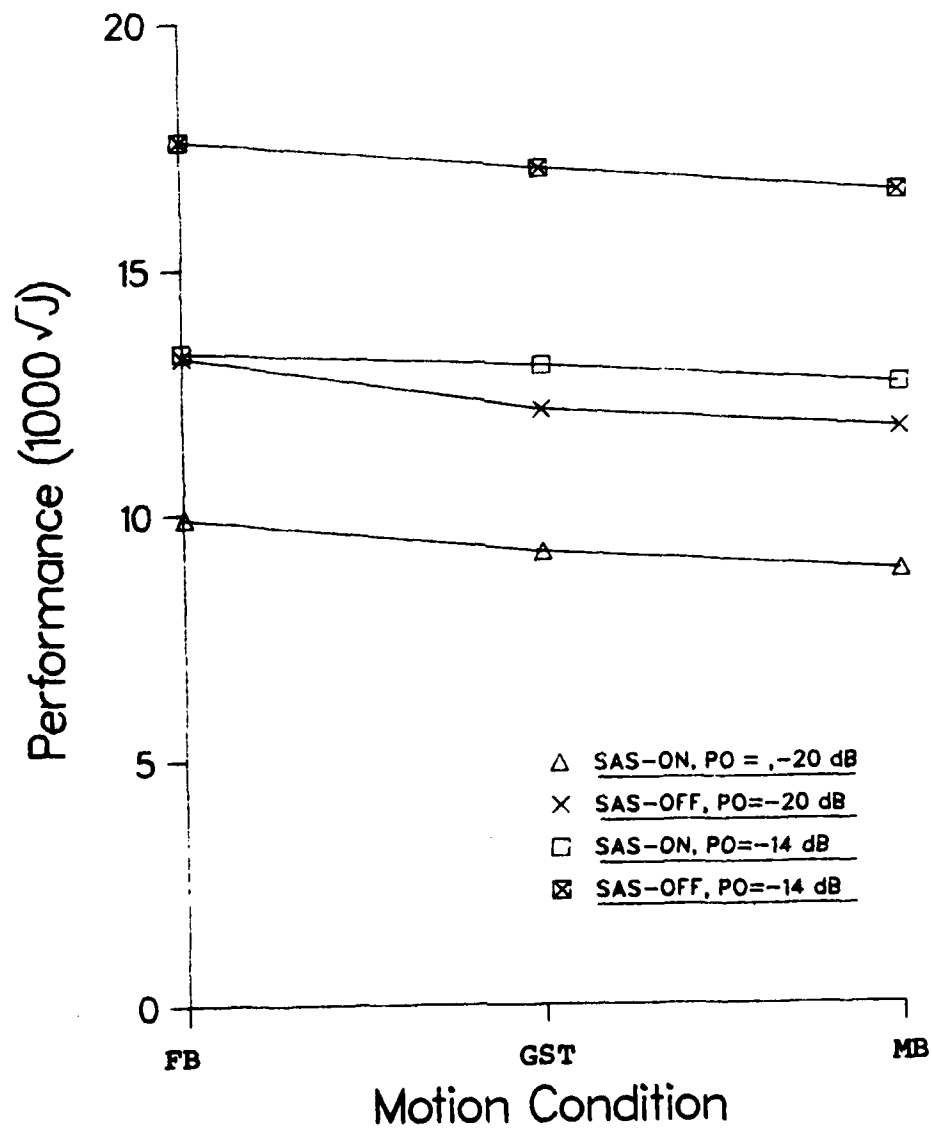


Figure 9. Effect of Motion Condition on Cruise Performance

a) Performance Score

## SECTION IV

## SUMMARY AND CONCLUSIONS

In this study, the results of an analytical investigation of pilot control of a "simulated" AV-8B (Harrier) aircraft were presented. The analysis was performed using a well-established pilot-vehicle model, namely the Optimal Control Model (OCM). The effects on closed-loop performance of aircraft configuration (SAS-ON or SAS-OFF) and flight condition (hover or cruise) and of simulator motion cueing condition (fixed-base, moving platform or g-seat) were all analyzed. In addition, the interaction between these conditions and the level of pilot attention and/or skill (or training) was investigated by means of a sensitivity analysis in which a parameter of the OCM (the observation noise/signal ratio) which can be related to these pilot factors was systematically varied.

The model analyses show that motion cues could be very significant in the Harrier hover control task for the unaugmented vehicle (SAS-OFF). The extreme sensitivity at high observation noise/signal ratios evidenced for this condition suggests that motion cues would be most important in early training (low skill levels) or when the pilot has other tasks to perform while attempting to hover. For the SAS-ON configuration, platform motion provides significant improvements in performance only if the pilot does not have to share attention between cues within the motion modality. Otherwise, the improvement provided by motion cues is marginal.

The model predicts that the addition of motion cues for the task of disturbance regulation in cruise does not result in a significant (i.e., greater than fifteen percent) improvement in performance for either SAS-ON or SAS-OFF configurations. This is true despite the (favorable) assumption of no attention-sharing within the motion modality. The result holds, moreover, for the range of observation noise/signal ratios considered. Indeed, for cruise the more skilled or the more attentive to the task is the pilot (i.e., the smaller the observation noise), the more beneficial the motion cues are for performance. These results, showing the relative unimportance of motion cues in cruise, help to explain why a motion platform is often deemed by pilots to be unnecessary for this flight condition.

An important result of the analysis is that provision of motion cues via a g-seat yields performance approaching that obtained with platform motion. Actually, the predicted differences between the two cueing methods are within the range of differences expected due to inter- or intra-pilot variability. It should be remembered, however, that the assumptions concerning the information available from a g-seat, as well as those concerning the quality of that information, are not as firmly based on data as the corresponding assumptions for platform motion.

The results discussed herein confirm again the dependence of motion effects on task parameters. Thus, they demonstrate the need for models to determine or specify motion requirements in a given situation. However, the results also indicate areas of research that should be addressed to enhance the model's utility for specifying simulator requirements. In particular, it would be desirable to conduct experiments to resolve the question of whether attention must be shared within the motion modality or, indeed, between the motion and the visual modalities. Another important research need is for data to determine more precisely the cues provided by a g-seat and the perceptual limitations associated with that device.

A research area that is more speculative arises from the results concerning sensitivity of performance in hover to observation noise. These results suggest that, early in training, the task be taught with the SAS-ON or, alternatively, one axis at a time (as is now sometimes done, with the instructor controlling the remaining axes). Once the trainees have been able to reduce their noise levels, one might add axes for manual control or consider hover without the SAS. One might conjecture on the basis of these model results that this regimen would mitigate some of the need for motion cues in training the hover task. Both the conjecture itself and the notion of using the model to explore methods of training appear to warrant further investigation.

We close with a note of caution. For the most part, we have examined the effects of motion cues on asymptotic performance. We have not investigated the impact of these cues on the rate of learning of the task. It must be remembered that providing motion cues in a training simulator might be cost effective if learning is thereby accelerated, even if asymptotic performance is not impacted. The effect of motion on rate of learning is another area in need of additional research.

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